NORTHEASTWARD-MOVING LOWS OVER EASTERN UNITED STATES, NOVEMBER 14–19, 1957

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1. INTRODUCTION

Three major storms whose history and initial development were very similar dominated the weather in the eastern half of the United States during the period of November 14–19, 1957. Each storm, categorized as Type IV by J. J. George [1] or E_L by California Institute of Technology [2], developed over the South-Central States and moved approximately northeastward accompanied by heavy precipitation.

This paper interprets some of the details revealed by analysis of each storm and the related pattern of instantaneous and maximum 24-hour precipitation. Surface, upper air, and some of the supplemental charts routinely prepared at NAWAC are used. One of the supplemental charts, called the "mean advection chart" (the 1000–500-mb. thickness lines superimposed on the 700-mb. contours), is shown in panels A and B of figures 2, 4, and 6. The relative strength and slope of the warm front and the cold front can readily be appraised qualitatively by noting the gradient of the thickness lines associated with fronts. In addition, for convenience and to save space, the area of maximum 500-mb. relative cyclonic vorticity [1] (prepared by Fjørtoft's [3] technique) and the areas of maximum 24-hour precipitation are shown on the advection charts.

In using the advection chart, NAWAC makes the assumption that the 700-mb. flow may be used to approximate the mean flow in the 1000–500-mb. layer and that the advection of thickness is generally proportional to the mean flow. This assumption saves time in applying Sutcliffe's theory of development and steering. In developing his theory, Sutcliffe [4] used basic equations and a few assumptions to derive mathematically the role of the thermal winds for the 1000–500-mb. layer in the steering and intensification of surface systems.

For convenience in referring to the three storms, they are designated as follows: Storm I, 0000 GMT November 14 through 1800 GMT November 15; Storm II, 1200 GMT November 15 through 0600 GMT November 17; Storm III, 0000 GMT November 18 through 1800 GMT November 19. Note that the early stages of Storm II overlap in time the final stages of Storm I.

[1] The value of the vorticity parameter presented on the composite "advection charts" as derived by Fjørtoft's technique is directly proportional to the relative cyclonic vorticity.

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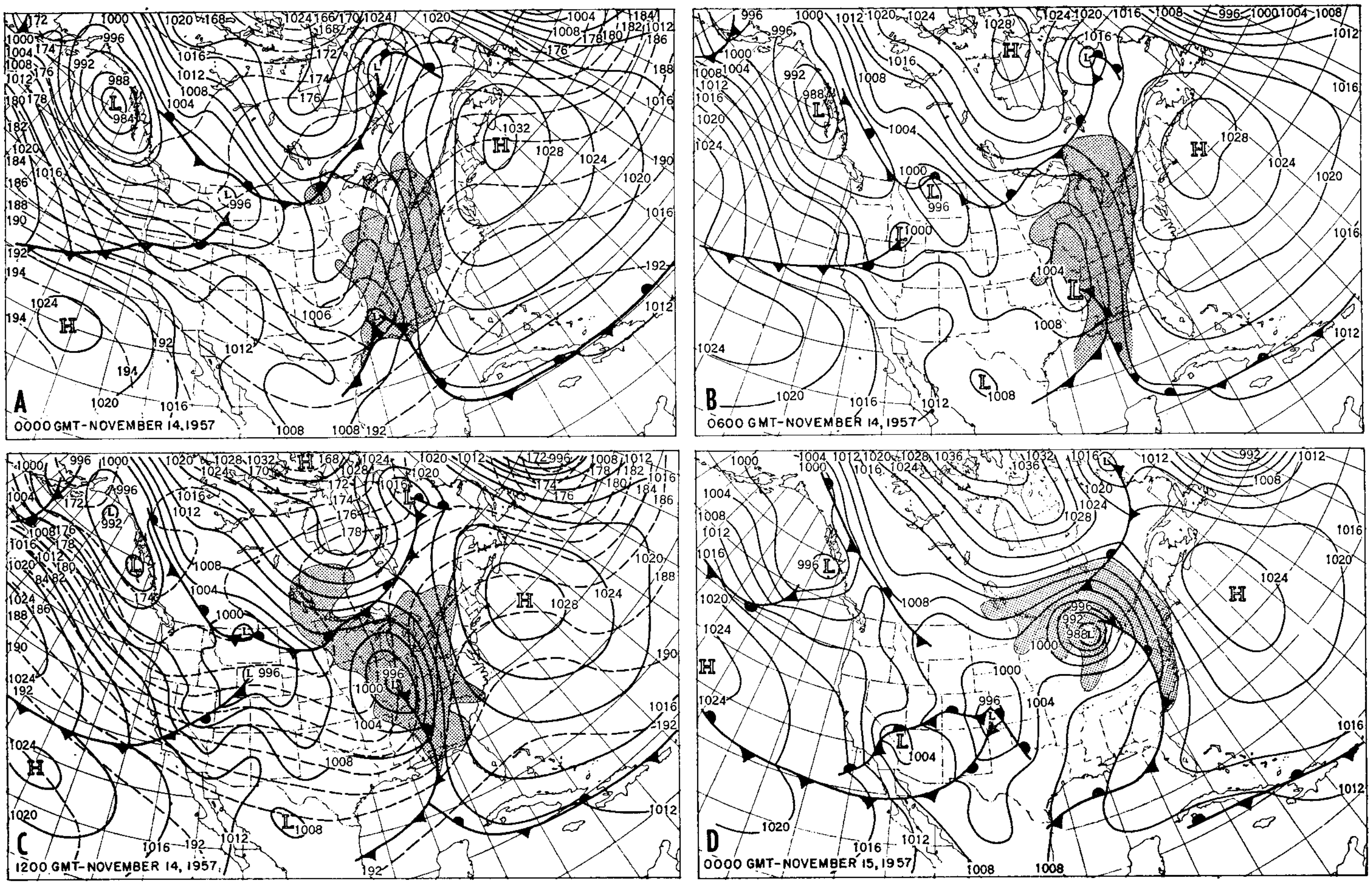
2. ANTECEDENT CONDITIONS

In general, the long-wave patterns for these cases were very similar. The 500-mb. space mean prepared by Fjørtoft's [3] technique for 0000 GMT on November 14 indicated a long-wave trough in the mid-Atlantic and another in the central United States. Zonal westerlies dominated the Pacific as one trough of small amplitude lay off the British Columbia coast and another near Kamchatka. By 1200 GMT on the 15th, the trough in the Atlantic showed little change; but slight retrogression was noted in the trough in the central United States as the trough near Kamchatka deepened and moved 10° eastward. As the wavelength of the long-wave pattern shortened and the amplitude of the pattern increased, the minor trough off the British Columbia coast continued to weaken and the long-wave troughs were reestablished in the central sections of the Atlantic and the United States on November 18.

Storm I crossed the Pacific coast of the United States as a weakening occluded frontal system and continued slowly eastward with little change in intensity until it approached the Texas Panhandle region. At 1200 GMT of the 13th some deepening of this system was noted as another occluded front (Storm II) was crossing the Northwestern States; however, a definite organized wave pattern in northwestern Louisiana was not induced until 0000 GMT of the 14th (fig. 1A). During the same time, Storm II had moved across the Pacific coast as an occluded front with its well-defined Low located over Montana. As Storm I moved northeastward toward the Great Lakes, little change in intensity was found in Storm II as it moved southeastward (figs. 1B, C) until it began slowly deepening in eastern Colorado (fig. 1D). By 1200 GMT of the 15th (fig. 3A), a well-defined center had formed in south-central Kansas as Storm I moved toward the southern portion of James Bay and another weak occlusion approached the Pacific Northwest (Storm III). At the surface, the movement of Storm III through the western States was completely masked although it was still a marked trough at 500 mb. (fig. 3C). A sharpening in this upper trough occurred with the approach of a fairly strong system off the Washington-Oregon coast (fig. 5A). Subsequent surface deepening through Texas resulted in a wave crest in eastern Oklahoma. By 1200 GMT on the



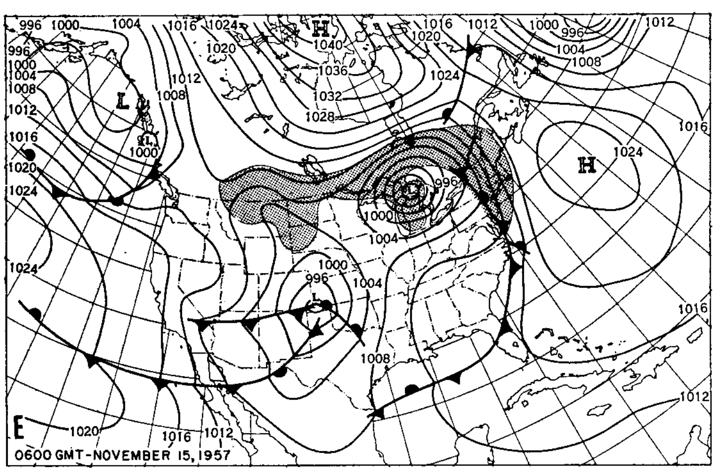


FIGURE 1.—Surface maps for Storm I with associated precipitation patterns (shaded). 500-mb. contours (dashed) are shown for the initial 12 hours on maps A and C.

18th, the strong surface Low (Storm III) had moved into southern Missouri (fig. 5C).

This conspectus of their histories illustrates the similarity of formation of all three cases which follows to some extent the sequence of events in the development of Colorado Type Lows as described by Jacobson et al. [5].

This type of storm (George Type IV or the final phases of CIT Type E_L) definitely poses a threat of excessive precipitation over the entire eastern half of the United States; therefore, some details of the storms and their differences as related to the maximum 24-hour precipitation anomalies are studied in the following sections.

3. STORM I

SYNOPTIC SITUATION

By 0000 GMT of the 14th (fig. 1A), a northeasterly movement of the Low in northern Louisiana (Storm I) was indicated by negative pressure tendencies over northern Mississippi, the positive tendencies over eastern Texas, and southwesterly flow at 500 mb. over the Low center; however, the magnitude of the isallobaric field indicated little deepening. The advection chart for Storm I (fig. 2A) at 0000 GMT on the 14th indicated that the strongest warm advection extended from eastern Louisiana southeastward through Alabama and north-northeastward toward the Great Lakes—generally over the area of current precipitation shown by the shading through the Mississippi and Ohio Valleys in figure 1A. The field of maximum relative cyclonic vorticity outlined in figure 2A by the +100-foot isoline was located upstream over Nebraska, Kansas, western Oklahoma, and western Texas, somewhat northwest of the 700-mb. trough. Apparent warm advection at 500 mb. upstream ahead

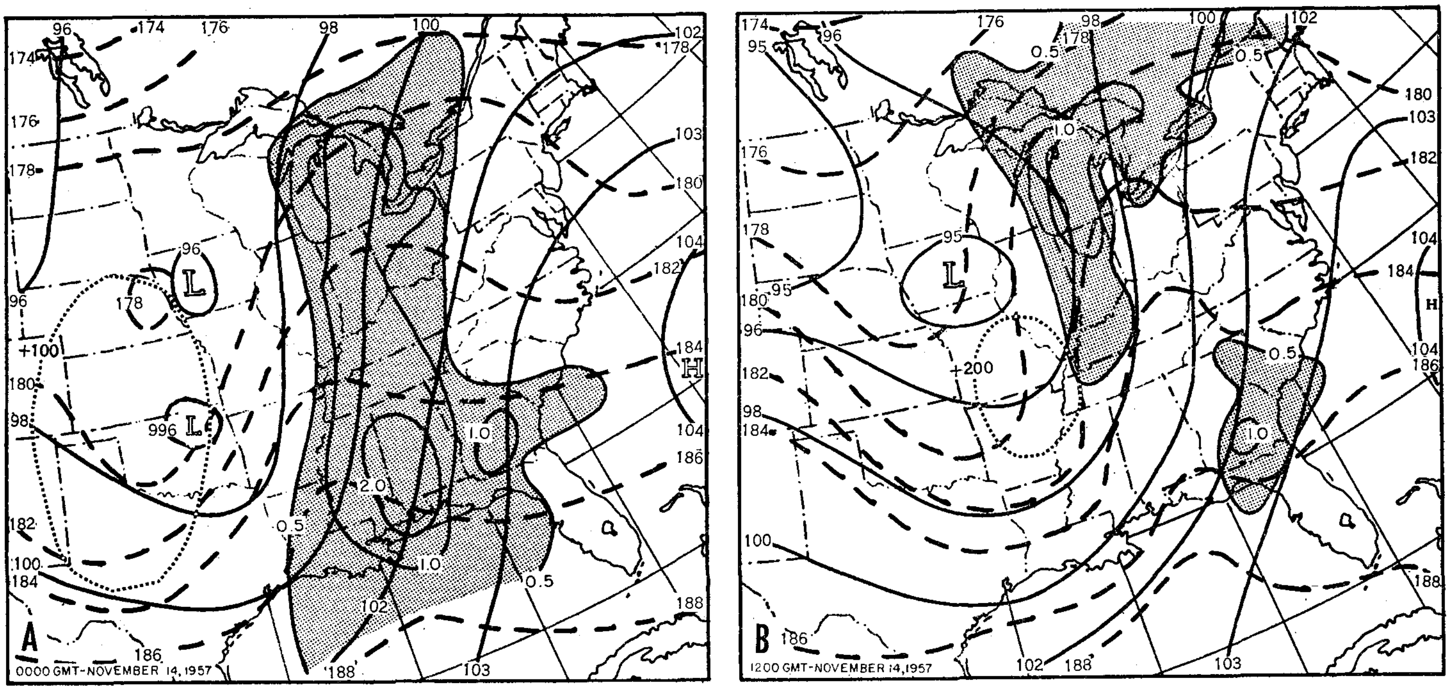


FIGURE 2.—Advection charts for Storm I with 700-mb. contours (solid), 1000–500-mb. thickness lines (dashed), areas of maximum precipitation ending 24 hours after chart (shaded), and areas of maximum relative vorticity according to Fjørtoft's method (dotted lines).

of the occluded system in northwestern United States suggested some sharpening of the upper trough in the central United States (increasing the curvature contribution to vorticity), whereas the wavelength and the strength of the flow upstream suggested some acceleration of the upper trough.

By 0600 GMT on the 14th (fig. 1B), either or both of these developments were indicated by the increasing area of the katallobaric field west of the surface center. By 1200 GMT (fig. 1C) the surface Low had deepened 8 mb. and moved northeastward at approximately 40 knots; the 500-mb. trough had deepened about 100 feet in the vicinity of Missouri and had moved closer to the surface center. The advection chart at this time (fig. 2B) showed still fairly strong warm advection east of the Mississippi River, but the flow through Louisiana and Texas was now parallel to the thickness pattern with a shallow cold zone indicated over northern Arkansas and Missouri. The maximum relative cyclonic vorticity also increased as indicated by the +200-foot isoline and moved more into phase with the 700-mb. trough. Since the cold advection term was decreasing in the southern portion of the trough, little change or flattening of the trough was expected; however, continued rapid movement of the trough was indicated by the strong upstream flow at both the 700- and 500-mb. levels.

The main contribution to further deepening of the Low apparently came from the upper-level advection of vorticity and the indicated warm advection ahead of the system (Petterssen [6]). Large surface tendencies to the east and north of the Low, now in eastern Illinois (fig. 1C), confirmed this. By 0000 GMT of the 15th (fig. 1D) the Low, then south of Sault Ste. Marie, had almost reached its maximum depth. In the next 6 hours it moved northeastward with little deepening (fig. 1E). At this time the intensity of the katallobaric field was equal to that of the anallobaric field. By 1200 GMT November 15 the cyclone became a cold Low as the cold air spread rapidly eastward south of the center in response to the acceleration of the upper trough south of the Low. This rapid motion eastward served to "cut off" the southerly or warm advection flow east of the surface system. Following this development the deepening ended. Figure 3B shows the Low as it filled near the tip of James Bay and as the remaining warm advection became associated with a secondary wave on the rapidly eastward-moving cold front off Nantucket.

MAXIMUM PRECIPITATION

The areas of maximum 24-hour precipitation in the three storms have been indicated on figures 2, 4, and 6. As Storm I was first developing in northern Louisiana (fig. 1A, 0000 GMT of the 14th), it produced a narrow but effective warm, moist, southwesterly influx of air off the western Gulf of Mexico. At 850 mb. (not shown), this narrow current was well delineated by the 10° C. isodrosotherm. The associated area of maximum 24-hour precipitation (from the north central Gulf States to the eastern Great Lakes region), including a sizable 2-inch region (over eastern Mississippi and western Alabama), is delineated in figure 2A. Note the axis of this maximum area and its relationship to the zone of maximum indicated warm advection; note also how this axis became more

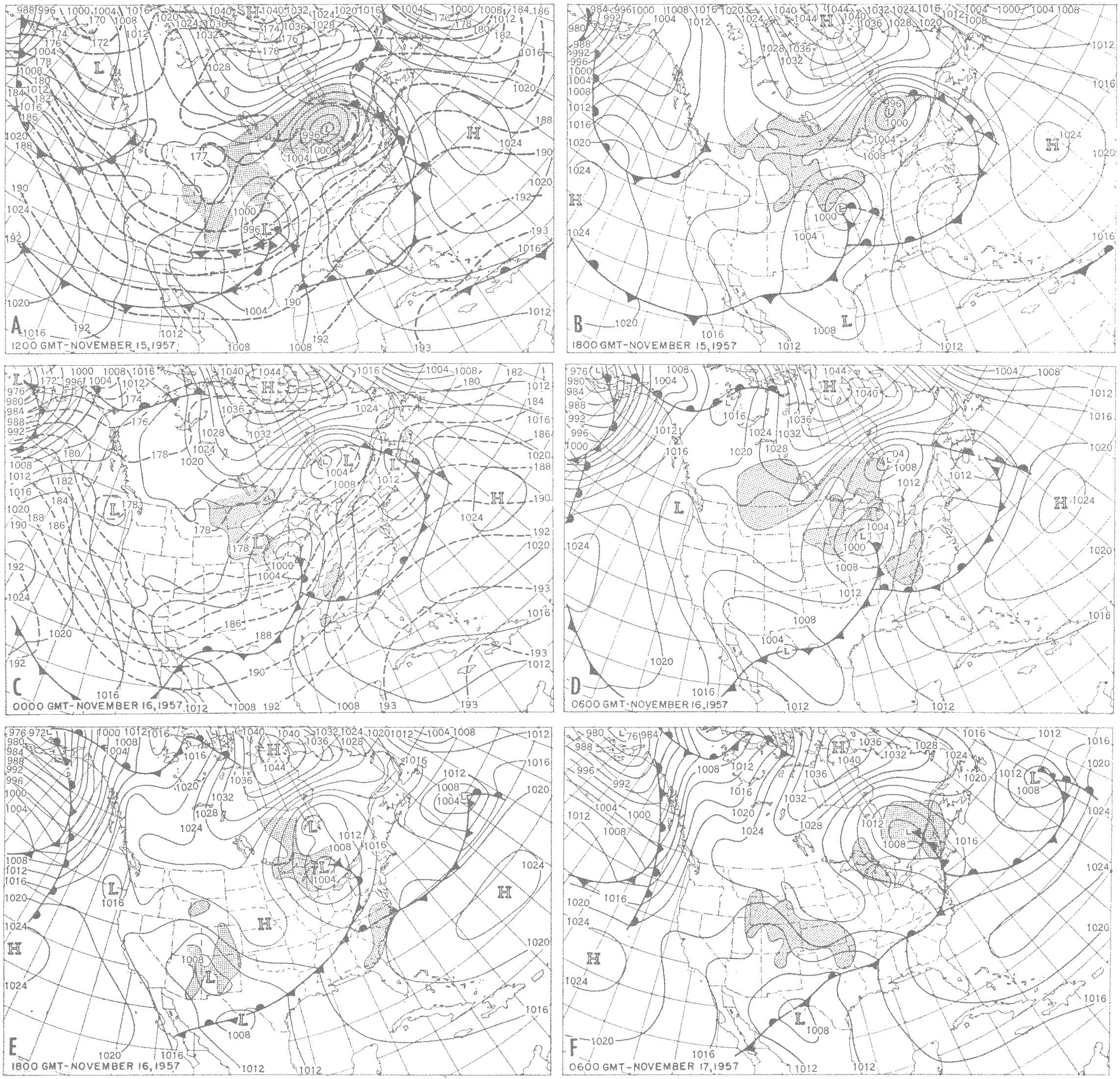


FIGURE 3.—Surface maps for Storm II with associated precipitation patterns (shaded). 500-mb. contours (dashed), are shown for the initial 12 hours on maps A and C.

closely related to the path of the deepening Low with time.

By 1200 GMT of the 14th (fig. 2B), the axis of maximum precipitation had split into two segments as the area of the 10° C. isodrosotherm at 850 mb. decreased to an even narrower zone near Mobile, Ala., with marked veering of the southerly flow at 850 mb. The lower portion of the maximum precipitation arêa moved generally eastward and lessened as the northern section developed an axis more in phase with the actual path of the rapidly deepening storm in eastern Illinois (fig. 1C). At the point of maximum deepening and intensification (fig. 1D) the axis of maximum precipitation of the northern portion (fig. 2B) coincided with the path of the deep Low. Note the increased gradient north of the 18,200-foot thickness (steeper slope of the warm front) in the vicinity of the eastern Great Lakes. Also note on the advection chart for this time the relationship of the axis of strongest warm advection (along the 10,000-foot contour) to the axis of maximum precipitation in this area. The lower portion

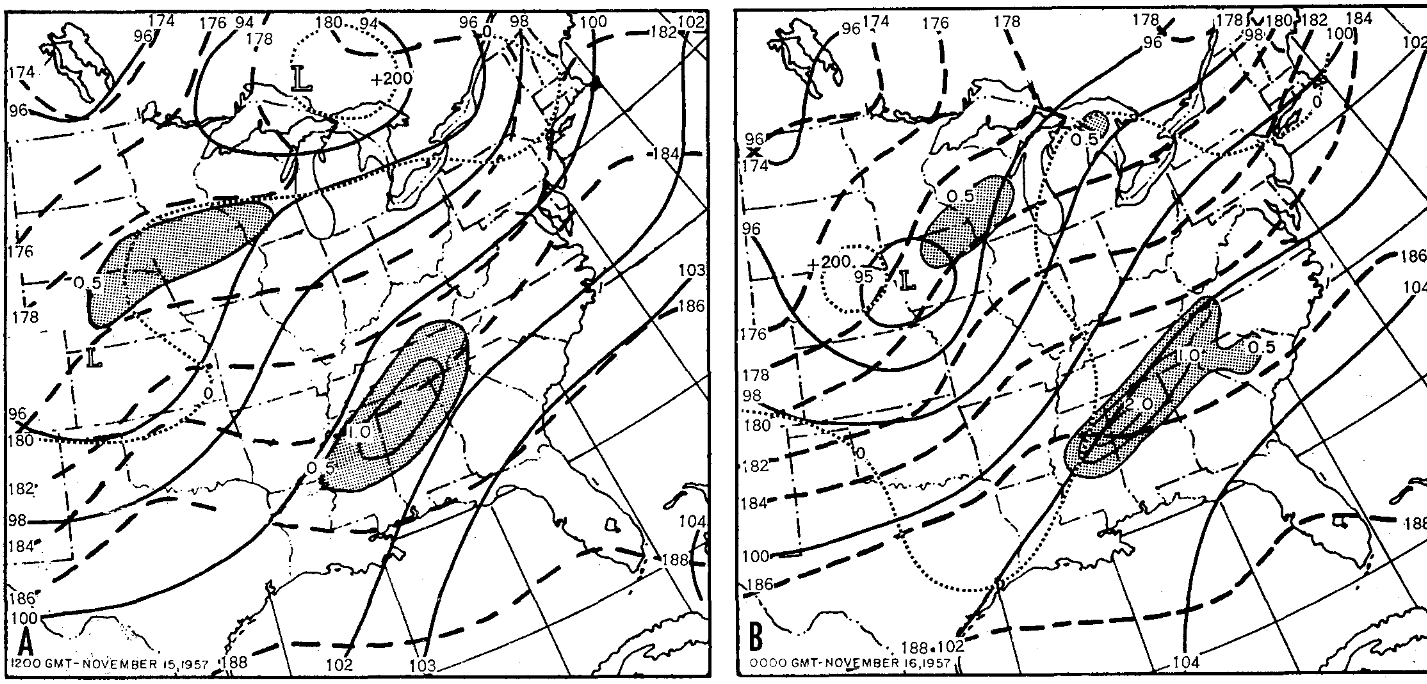


FIGURE 4.—Advection charts for Storm II with 700-mb. contours (solid), 1000–500-mb. thickness lines (dashed), areas of maximum precipitation ending 24 hours after chart (shaded), and area of maximum relative vorticity according to Fjørtoft's method (dotted lines).

or cell of the maximum zone of precipitation contained primarily heavy showers and thundershowers which were "triggered" by lifting along the warm and cold fronts (figs. 1A–D).

On the stability index chart for 0000 GMT of the 14th (not shown), an area of zero values lay over Louisiana, approximately the area of the warm sector. By 1200 GMT, this area was depressed southward along the Gulf coast. (See fig. 1, D and E). Note the relationship to the anticyclonic curvature of the 18,600-foot thickness line (fig. 2B) which encompassed the surface frontal structure. As the thickness gradient became weaker, suggesting a significant decrease in warm advection, the magnitude of surface pressure tendencies ahead of the front diminished along the eastern Gulf States. In time, cold advection decreased with consequent filling or flattening of the upper trough. This brought further weakening of surface negative pressure tendencies and produced a filling of the surface frontal trough over the southeastern United States (fig. 1, D and E), thereby decreasing the influx of southerly moist air and reducing the "trigger action" of the cold front.

4. STORM II

SYNOPTIC SITUATION

At 1200 GMT of the 15th (fig. 3A), a weak occluded system was located off the west coast with indications of further weakening as another strong Low was moving toward the western Aleutian chain. Storm I at this time was centered northeast of Sault Ste. Marie and Storm II was a well-developed Low in south-central Kansas. The axis of the surface pressure tendencies associated with Storm II was oriented northeast-southwest and indicated a northeastward movement with little change in intensity. At 500 mb. a fairly broad trough over the western United States was associated with Storm II while a shallow ridge extended southeastward from Ohio to the Carolinas. The upstream flow had a fairly long fetch but was broken up by two troughs, one over the extreme western States and the other, a weak and shallow trough just east of Ship "Papa" (50° N., 145° W.) associated with the weak surface occluded front just off the west coast.

On the advection chart for this time (fig. 4A), the pattern associated with Storm II showed a relatively steep frontal slope with marked anticyclonic curvature; however, note the shallow weak warm advection along the warm sector side of the 18,600-foot thickness line. The strongest warm advection was located due east of the surface Low in eastern Kansas and northern Missouri. Note the contrast of the north-south amplitude of the warm advection area with the warm advection area for Storm I shown in figure 2A. The cold advection associated with Storm II was in the Texas Panhandle and western Texas and was of approximately the same magnitude as the warm advection. Further investigation of these two cases revealed some contrast in the magnitude of maximum relative cyclonic vorticity: in figure 2A the +100-foot isoline is located upstream over Nebraska, Kansas, western Oklahoma, and western Texas; in figure 4A the zero isoline suggests that the maximum relative cyclonic vorticity of Storm II was very shallow and less than +100 feet.

At this time, the precipitation pattern of Storm II was

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located primarily under and to the west of the strongest curvature of the surface isobars in the extreme northern portion of the system. An inspection of the soundings southwest of the polar warm front showed that the warm sector air mass was very dry and would require considerable lifting for saturation. A shallow slope of approximately 1/125 for the warm front was found, which might suggest why the precipitation was occurring so far north of the system at this time. A few showers reported near the southeastern coast of Texas suggested the approach of more unstable tropical air.

The system continued moving northeastward to northeastern Kansas with some filling as the northern polar frontal system became diffuse and weakened (fig. 3B), another indication of further weakening of the warm and cold advection aloft. As the maritime polar cold frontal trough south of the Low moved eastward through central Texas, the warm front moved from the western Gulf of Mexico northward to southern Arkansas, central Mississippi, Alabama, and Georgia. Surface tendencies of Storm II had a well-defined northeast-southwest axis and indicated a continued northeastward movement of 25 knots with further weak filling. The precipitation pattern was still north of the surface Low center but had spread eastward from Nebraska to northern Iowa while widely scattered showers persisted along the western Gulf. By 0000 GMT of the 16th, the Low had moved to extreme northern Missouri with further weak filling (fig. 3C). The cold front moved slowly through Texas and the warm front advanced to central Arkansas. The 500-mb. chart showed that some sharpening of the upper trough had occurred in Nebraska as a closed Low formed in southern South Dakota. This was reflected on the advection chart (fig. 4B) as a small +200-foot area of relative cyclonic vorticity formed just west of the 700-mb. Low and as the region of positive vorticity extended southward through eastern Texas. This increase in amplitude or sharpening of the trough resulted from height rises (ridging) over New Mexico and Colorado following marked deepening over Nevada and southern California. This change over the Southwest—a process known as discontinuous retrogression of the long-wave pattern—was induced by large height rises east of Ship "Papa" as a very strong occluded system moved toward the Gulf of Alaska.

As the experienced forecaster would have expected at this point, the original trough in the central United States continued to move eastward as a minor or short wave while the new trough in the southwestern United States assumed major proportions with the development of a new storm on the polar front. The surface anallobaric field now intensified as rises also occurred ahead of the cold front in the warm Gulf air. The katallobaric field weakened mainly east-northeast of the center. Showers and thundershowers began just north of the warm front in Mississippi, Alabama, and western Tennessee. The advection chart for this time (fig. 4B) indicated a decrease in the warm and cold advection south of latitude 34° N. and a marked decrease in anticyclonic curvature of thickness lines, especially the 18,600-foot line. The strongest warm advection, though weak, was east of the Low center and well north of the surface warm front; and with time, this advection continued to decrease the slope of the warm front. Eastward acceleration of the surface occlusion in Missouri was suggested by the apparent stronger advection and the increased westerly component at 500 mb. through Kansas.

With flow at 700 mb. south of Kansas parallel to the thickness lines (no further cold advection southward), with positive surface tendencies ahead of the cold front, and with falling surface tendencies over the Southwest, the front in eastern Texas became quasi-stationary. Figures 3 D and E show that Storm II continued to fill and moved northeastward as its associated occluded front moved rapidly toward the east coast. The precipitation pattern associated with this Low remained north of the center, whereas the unstable precipitation moved eastward and remained near the warm front. The cold front moved slowly eastward through northern Mississippi and central Tennessee before stalling. By 0600 GMT of the 17th (fig. 3F) the polar front in eastern Texas began moving northward as a moderate warm front, as deepening occurred in southwestern Texas and as the ridge through the Dakotas southeastward to Kentucky strengthened. Overrunning precipitation north of the warm front fell in eastern Oklahoma northwestward through Wyoming.

MAXIMUM PRECIPITATION

The 1-inch isohyet of 24-hour maximum precipitation ending at 1200 GMT of the 16th associated with Storm II (fig. 4A) was well to the east of the maximum anticyclonically curved 18,400- and 18,600-foot thickness lines. One marked difference between the advection charts for Storm II (fig. 4A) and for Storm I (fig. 2A) was that the 700-mb. trough over Texas was somewhat farther east and much sharper in Storm I. Warm and cold advection on the 18,600-foot thickness line was much stronger in Storm I and the thickness ridge was somewhat farther east of the 700-mb. trough line. It has long been known that the influx of warm, moist air from the western Gulf of Mexico depends on the "opening-up" or southward deepening of the polar trough through eastern Texas. Experience has also shown that a definite influx of maritime tropical air occurs whenever the flow aloft in this air backs to a direction south of west (preferably southwest to south) in eastern Texas. This flow is frequently associated with the 10,000-foot contour at 700 mb. or the 18,800-foot contour at 500 mb. The greater the amplitude of the contour and the stronger the geostrophic flow east of the trough line, the greater the moist influx. As previously noted, advection for this case indicated that either little change or filling in the southern portion of the trough in Texas was to be expected while the northern portion accelerated and moved eastward. The resultant predominantly westerly flow through Texas was dry along the 10,000-foot contour; the influx of moisture in Storm II was found along the 10,100- or 10,200-foot contour.

The 850-mb. chart for this time showed the +10° C. isodrosotherm located over southeastern Texas and Louisiana; the stability index chart delineated an area of zero stability encompassing southeastern Texas and western Louisiana. Precipitation began as showers and thunderstorms near the warm front (18,600-foot thickness contour) in northern Mississippi and western Tennessee 12 hours after the time of the advection chart, figure 4A. The time of this outbreak of precipitation corresponded with a northeasterly 12-hour movement (at 25 knots) of the center of moist unstable air from western Louisiana to the downstream position of strongest thermal wind shear along the 18,600-foot thickness line (fig. 4B). The continued northeastward movement of Storm II and the filling of the frontal trough continued to decrease the warm advection and terminated the maximum amounts of precipitation in the western Carolinas. The decrease of warm advection was borne out by the weakening of the isobaric gradient across the Gulf of Mexico in the surface maps of figures 3 C–F. The difference in intensity of the maximum precipitation area on figure 4B from that in figure 4A occurred because the precipitation began in the mid-period of figure 4A and moved eastward so slowly it overlapped and persisted for a longer period in figure 4B.

5. STORM III

SYNOPTIC SITUATION

As the short-wave trough, associated with the surface occluded front, moved over the ridge in the eastern Pacific, the deepening trough over the southwestern United States (discussed above) continued eastward. As this latter trough in western New Mexico became a major feature of the upper air it provided the energy for the development of Storm III on the polar front in northeastern Texas (fig. 5A).

The advection chart at this time (fig. 6A) indicated a very strong thickness gradient associated with the cold front through Texas, a fairly steep gradient ahead of the warm front, and a secondary packing of the thickness lines through northern Missouri and Illinois. The area of maximum positive relative vorticity was encircled by a small +200-foot isoline in northeastern Colorado; however, the area enclosed by the zero line was quite large with a probable secondary maximum over New Mexico. This secondary maximum of positive relative vorticity appeared to be in phase with the 700-mb. trough. It suggested that any further eastward movement of the southern portion of the 500-mb. trough, or the vorticity maximum over New Mexico, would produce marked instability in the level between 700 and 500 mb. and would probably result in an accelerated movement of the 700-mb. trough through Texas and likewise an increase in the cold advection term. Warm advection along the Oregon and northern California coast indicated some continued sharpening or southward deepening of this trough, whereas the strong zonal flow through northern Mexico suggested an eastward movement.

Some evidence of the unstable characteristics of the system was manifested on the surface chart by a band of fairly heavy precipitation in western Texas. (El Paso reported a thunderstorm to the east.) The southerly flow of definitely maritime tropical air off the western Gulf was heavily laden with moisture; showers and thundershowers occurred in the flow through Louisiana and Mississippi and along the leading edge of the warm front (figs. 5A and B). The main over-running precipitation was generally west of the wave crest, due to some extent to upslope flow east of the Divide.

The fields of strongest warm and cold advection suggested a definite northeasterly movement and further deepening of the surface Low. By 1200 GMT on November 18 (fig. 5C), the Low was well developed; it had deepened 4 mb. and the isallobaric field indicated further deepening. The orientation of the isallobars also suggested a more northerly movement of the Low. The katallobaric field to the north of the Low had falls of 5 to 6 mb. per three hours. The cold front, under the influence of increasing isobaric gradient along it, accelerated eastward as the warm front moved more slowly northward to southern Missouri and western Kentucky. Thunderstorms continued in the area along the warm front and along the entire length of the cold front. In general, the precipitation pattern enveloped the system; however, the pattern spread through northern Illinois and southern Wisconsin and all of Iowa (under and to the west of the strongest surface isobaric curvature and associated with the strong katallobaric field north of the Low).

From figure 6B, the advection chart for 1200 GMT, the thermal wind shear along the 18,600-foot thickness contour still suggested a warm front in southern Missouri and western Kentucky; however, it had definitely weakened as the stronger gradient in northern Illinois became more prominent. The strong warm advection indicated by this stronger gradient coincided with the increasing katallobaric field noted above. Cold advection through Oklahoma and eastern Texas had definitely increased and insured a strong surface cold front passage through the Gulf States, and also tended to further deepen or maintain the amplitude of the 500-mb. trough. The positive relative vorticity maximum shown in figure 6B had increased to a +200-foot value of fair size located south-southwest of the 700-mb. Low which had also deepened some 200 feet. Warm advection was still very strong and thus suggested a more northerly movement of the Low. Sustained strong cold advection across the Gulf, plus the advection of relative cyclonic vorticity at 500 mb., continued to deepen the system until it occluded as the cold advection persisted eastward and cut off the influx of warm air. In figure 5, D and E, the Low continued to deepen approximately 25 mb. as it turned sharply north-

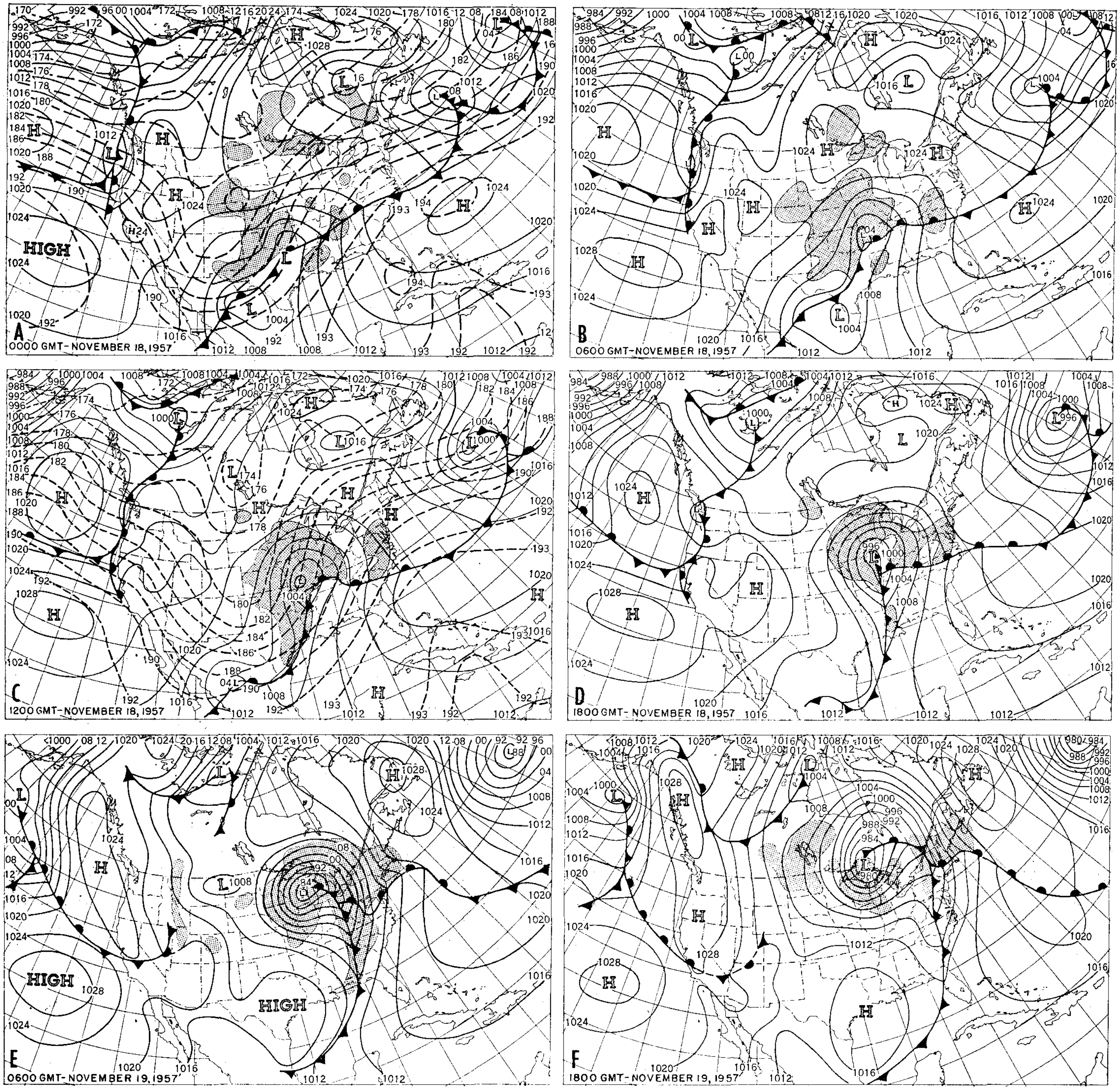

FIGURE 5.—Surface maps for Storm III with associated precipitation patterns (shaded). 500-mb. contours (dashed), are shown for the initial 12 hours on maps A and C.

ward across the western Great Lakes. By 1800 GMT of the 19th (fig. 5F), deepening had begun to level off with positive pressure tendencies spreading east of the Low as the cold front approached the Eastern Seaboard of the United States.

MAXIMUM PRECIPITATION

By 0300 GMT on November 18, thunderstorms began developing near Waco, Tex. along the leading edge of the cold front and also in eastern Oklahoma and northern Arkansas (north and east of the surface wave crest and under the strong warm advection on the 18,600-foot thickness contour.) Three hours later (fig. 5B), as the surface wave developed a closed circulation with a marked increase in shear across the cold front in eastern Texas, thunderstorms and heavy showers had occurred along the entire length of the front. Thunderstorms continued along the leading edge of the warm front in Arkansas and western Tennessee as over-running precipitation gradually appeared north of the band of thunderstorms. By 1200

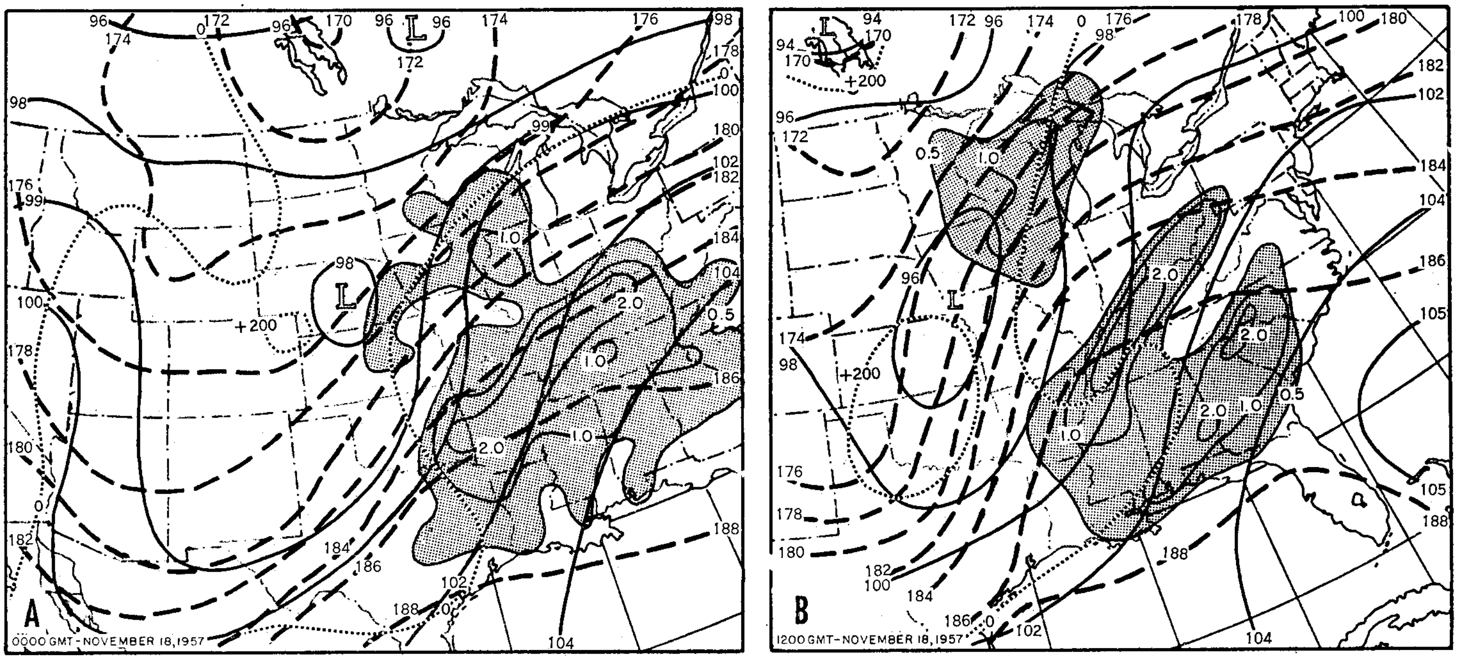

FIGURE 6.—Advection charts for Storm III with 700-mb. contours (solid), 1000–500-mb. thickness lines (dashed), areas of maximum precipitation ending 24 hours after chart (shaded), and area of maximum relative vorticity according to Fjørtoft's method (dotted lines).

GMT (fig. 5C) the over-running precipitation spread northward and westward as the warm front, under the influence of stronger southerly flow along it, moved northward to southern Missouri and western Kentucky. Thunderstorms with very heavy precipitation continued along the front in this area. In general the precipitation pattern enveloped the system; however, a diminishing precipitation was observed through central Missouri and central Illinois and an area of increasing precipitation was found through northern Illinois, southern Wisconsin, and all of Iowa. This region of increasing precipitation was under and to the west of the larger tendency falls.

The advection chart for 1200 GMT (fig. 6B) still gave good evidence for the warm front in southern Missouri and western Kentucky; however, the warm front had definitely weakened as the stronger gradient in northern Illinois and Indiana became more prominent. The strong warm advection associated with this steeper gradient coincided with the increasing rain pattern and large falling tendencies noted above. Some aspects of the diminishing rain pattern through central Missouri and central Illinois can be explained by the advection chart which shows a narrow flow parallel to the thickness pattern (no advective qualities) through Missouri.

At 0000 GMT of the 18th, the total precipitable water[2] associated with the southerly flow was well over 1 inch, and by 1200 GMT the 1-inch contour was carried northward to the latitude of the Low in northern Illinois and a 1.50-inch area was located over western and central Tennessee. The 24-hour maximum precipitation pattern which ended at 0000 GMT of the 18th (fig. 6A) was located over eastern Texas, western Louisiana, northeastward through southeastern Missouri, southern Illinois, southern Indiana, and western Kentucky, with a lobe shown over northern Illinois. The major axis of this maximum (2 inches or more) followed the movement of the peak of the warm sector as it moved north and eastward. The forming lobe was probably due to the main over-running associated with the steeper gradient of thickness values over northern Illinois and Indiana plus the intense isobaric curvature of the deepening surface Low. By 1200 GMT the 24-hour precipitation pattern (fig. 6B) displayed maxima along three axes: (1) The northernmost axis in northern Illinois (fig. 6A) coincided with the path of this deepening Low. (2) Another axis followed the path of the apex of the warm sector and overlapped values of the maximum precipitation indicated in figure 6A. (3) The third axis began as an intense area of thunderstorms along the cold front in eastern Texas and western Louisiana (fig. 5, C, D, and E) and moved eastward with the cold front.

6. CONCLUSIONS

Three major storms whose history and initial development were very similar have been discussed. An attempt has been made to show how further developments of each storm depended on the changes in the 1000–500-mb. thickness patterns, and how the instantaneous flow could be used to indicate how such changes would occur. One characteristic of this type of storm is that the influx of moist, unstable, maritime tropical air is induced into the storm circulation as it develops east of the Divide with the rate of influx varying as the development varies.

Deepening or increased development of this type of storm appears to be related to the following three parameters:

[2] On November 16 a precipitable water chart was started at NAWAC.

(1) The current gradient of the thickness contours.

(2a) The area and magnitude of cold advection associated with the Low. (The greater the amplitude of the cold advection, the greater the chance for deepening.)

(2b) The area and magnitude of warm advection associated with the Low. (The greater the amplitude of warm advection and the closer the center of advection lies to the 18,600-foot thickness line or warm sector thickness contours, the greater the chance for development. The warm advection may actually increase following the occurrence of strong cold advection west of the wave crest as in Storm III.)

(3) The advection of upper-level (500 mb.) relative cyclonic vorticity. (The advection can be determined by the Fjørtoft [3] space mean chart with the trend or acceleration of vorticity determined from consecutive charts and modified by subjective baroclinic changes as indicated on the instantaneous advection chart. In the absence of a Fjørtoft space mean chart one may check the movement of the 500-mb. Low or trough by other objective techniques.)

Areas of maximum 24-hour precipitation are directly related to the rate of influx of moist, unstable, or conditionally unstable, maritime tropical air and with the thickness gradient of the warm front. In time, the maximum precipitation moves along a path prescribed by the movement of the areas of warm advection. With intensification of the surface Low, areas of secondary maxima may form well north of the warm front and become aligned with the path of the Low (diminishing as the Low occludes). The secondary maxima may also form ahead of the cold front associated with a steep thickness gradient and strong cold advection, and they are frequently associated with the axis of strongest flow in the warm sector.

ACKNOWLEDGMENTS

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